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88-Inch Cyclotron Operations

C.M. Lyneis

The 88-Inch Cyclotron is a versatile and reliable accelerator of beams from hydrogen to uranium. It is operated by Lawrence Berkeley National Laboratory (LBNL) as a national facility in support of the U.S. Department of Energy programs in nuclear science. Forefront scientific research in nuclear structure, heavy elements, proton-rich nuclei, nuclear astrophysics, fundamental symmetries, and reaction mechanisms is carried out. During FY97, a total of 332 users took part in experiments utilizing 6243 hours of beam on target. They came from 15 universities, 5 DOE National Laboratories, 20 foreign institutions. There were 150 scientists and 69 students participating in nuclear science experiments and 113 scientist and engineers participating in non-nuclear science experiments. The Cyclotron also provides beams for the application of nuclear techniques to other areas of research, including biology and medicine and industrial applications. Industrial partners from aerospace and semiconductor corporations, as well as from NASA, DOE, and DOD laboratories, use beams from the Cyclotron to study the interaction of ions in microcircuits, simulating the cosmic-ray environment in space.

Accelerator Use

The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory produced a record number of research hours in FY97, thereby maximizing the scientific opportunities with the Gammasphere detector prior to its move to Argonne National Laboratory. The research time (beam on target) in FY97 was 6243 hours, up more than 1000 hours compared to earlier years; more than 3800 hours of that time went for research with Gammasphere. The increase in the number of hours was due to more efficient cyclotron tuning, a reduced maintenance schedule, high machine reliability and an extended operating schedule. The Accelerator Operation Summary (Table 1) shows that in FY97 86.5% of the scheduled time was used for research (beam on target) while the remaining time was divided between tuning (8.5%), machine studies (1.6%), and unscheduled maintenance (3.6%). Nuclear research accounted for 5233 research hours, applied research for 894 hours, biology for 90 hours and high energy physics for 27 hours. The largest share of nuclear research beam time (3827 hours) went to Gammasphere experiments. The applied research—in

partnership with the aerospace industry, NASA, DOE, and DOD laboratories—consisted of two parts: (1) testing of microelectronics by using cyclotron beams to simulate space radiation, and (2) calibrating detectors for use in space flights. The biology research was done primarily in support of the NASA NSCORT program.

In FY98 the cyclotron will operate on a 20 eight-hour shifts/week schedule, but there will be more scheduled down time to upgrade internal components which affect the vacuum, to perform maintenance deferred from FY97 and to modify the facility to accommodate the new detectors, the Berkeley Gas-Filled Spectrometer and the 8-PI detector. More time will also be allotted to machine studies so that high intensity light-ion beams can be developed for the heavy-element research utilizing the BGS.

Ions, Energies, and Intensities

The cyclotron, fed by the ECR sources, provides a wide range of ions, energies, and intensities and most elements can be accelerated. Using the low and high temperature ovens in the ECR sources, most elements can be accelerated. To date 42 elements have been accelerated including every element from hydrogen to zinc. The beams listed in Table 2 were developed in support of the research programs. The isotopes which are run from natural feeds are listed in parentheses. In addition, many ions have been run using isotopically enriched source materials including ^3He , ^{13}C , ^{15}N , ^{18}O , $^{21,22}\text{Ne}$, $^{33,34,36}\text{S}$, $^{44,48}\text{Ca}$, ^{64}Ni , ^{70}Ge , $^{78,86}\text{Kr}$, ^{136}Xe , and ^{154}Sm . The most recent addition to the beam list was ^{96}Zr which was used by the University of Rochester group in conjunction with Gammasphere and the PPAC detector. A special tungsten crucible was developed to use the isotopically enriched zirconium metal.

The variety of beams, energies and intensities described in Table 2 has been developed in support of the research programs. Heavy element radiochemistry experiments require intense (several μA) heavy-ion beams up to mass 48 at 6-8 MeV/nucleon. Groups studying heavy-ion reaction mechanisms and complex fragmentation of highly excited nuclei use higher energy beams such as nitrogen and oxygen at 32 MeV/nucleon, neon at 25 MeV/nucleon, and krypton at 13 MeV/nucleon as well as light-ion beams of ^3He and ^4He over a wide energy range. Light-ion beams are also frequently utilized by other groups. For example, the laser trapping of radioactive beams uses 25 MeV proton beams to produce the ^{21}Na . The study of β -delayed proton emission requires several μA beams of ^3He at 40 to 110 MeV. The nuclear astrophysics group typically uses beams of protons, deuterons, ^3He and ^4He at 8-25 MeV/nucleon.

ECR Ion Source Development

A new very high magnetic field superconducting ECR ion source, the Third Generation ECR is under development at the Cyclotron. It will boost the maximum energies and intensities for heavy ions from the cyclotron particularly for ions mass 160 and above. Recent progress on ECR ion sources indicates that significantly higher performance can be obtained by incorporating very strong magnetic fields to improve the plasma confinement and by using multiple frequency heating to enhanced electron heating. The design includes a plasma chamber made from aluminum to provide additional cold electrons, three separate microwave feeds to allow multiple-frequency plasma heating (at 10, 14 and 18 GHz) and very high magnetic mirror fields. The design calls for mirror fields of 4 T at injection and 3 T at extraction and for a radial field strength at the wall of 2.4 T. The prototype superconducting magnet structure with three solenoid coils and six race track coils with iron poles forming the sextupole was constructed with FY96 LDRD funds and was tested in a vertical dewar last summer. The prototype magnet performance verified that the required fields can be achieved, but that improved clamping will be needed for the production model to decrease the number of quenches required to reach full field.

The first phase of the AIP project (FY97) is focused on completion of the production superconducting solenoids and sextupole and test operation in a vertical dewar. The second phase (FY98) will develop the horizontal cryostat, helium batch fill system, iron yoke for the magnet and verify the system meets the required cryogenic and magnetic field specifications. The third phase (FY99) will bring the Third Generation ECR into test operation with a single microwave klystron and beam analysis system. In phase 4 the source will be brought into operation with the cyclotron. Major components will include two additional microwave klystrons to provide the multiple frequency heating, a cryo-cooler to provide continuous operation and the beam optics elements to inject beam into the cyclotron.

Radioactive Beam Technology

The 88 Operations group is collaborating on two projects which involve the production, transportation and ionization of radioactive atoms. The Berkeley Experiments with Accelerated Radioactive Species (BEARS) is developing the technology for a gas-jet coupled radioactive beam system which utilizes the LBNL ECR to ionize the radioactive ions. This project is described in the Heavy Ion Research Section of this annual report. The second project, the ^{14}O experiment is a collaboration between the Ion Beam Technology group from AFRD, the Weak Interactions and Fundamental Symmetries group in NSD and 88 Operations. The goal is to produce ^{14}O using the cyclotron, transport it through a vacuum line as CO to a multicusp source where it will be ionized and accelerated to 30 kV

and then implanted to provide an ^{14}O source for beta shape spectrum measurements. Assembly of the system is underway and first radioactive ion beams are scheduled for the spring for 1998.

Other Accelerator Improvement Projects (AIP) at the 88-Inch Cyclotron

The vacuum system for the 88-Inch Cyclotron has been upgraded by the addition of a new cryopanel (the south port cryo) and the installation of a second CTI-1400 helium refrigerator and compressor. The south port cryo panel has a calculated pumping speed of 15,000 l/s and approximately doubles the pumping speed in the cyclotron main tank. The helium refrigerator and compressor had previously been used at the Bevalac and now complement the existing 88 system, provide additional cooling capacity and reliability. A new cross connect system allows using either of the helium compressors with either of the helium refrigerators and either refrigerator can be used to cool the old or new cryopanel. Recently a series of test were made to measure the improvement in the vacuum and the beam transmission when the south port cryo was turned on. The pressure in the extraction region decreased from 1.2×10^{-6} to 0.75×10^{-7} Torr and the transmission through the cyclotron increased from 3.8% to 6.2% for $^{136}\text{Xe}^{27+}$ at 603 MeV and from 1.4% to 4.3% for $^{209}\text{Bi}^{41+}$ at 904 MeV. The $^{209}\text{Bi}^{41+}$ intensity on the beam stop was 92 enA or 2.24 particle nA. As expected the greatest percentage gains in transmission were for the heaviest highest charge ions which are produced by the upgraded AECS source.

User Support

The Research Coordination Group provides information, assistance, and coordination to users of the 88-Inch Cyclotron. It is the main contact between the Cyclotron operations staff and outside users. As such, the group is responsible for developing and maintaining experimental facilities at the Cyclotron, and for making these facilities attractive to a diverse group of users from around the country and, in some cases, from around the world.

Our users fall into two classes: (1) scientific users whose experimental proposals are reviewed by a Program Advisory Committee (PAC) and who are awarded time based on the scientific merits of their proposals (or who are awarded discretionary time by the Cyclotron Head), and (2) industrial users who purchase beam time for their own proprietary use.

The Research Coordination Group coordinates the PAC, which meets two-three times a year to review proposals for beam time, and schedules beam time. It sponsors an annual users' meeting at the fall meeting of the Division of Nuclear Physics of the American Physical Society. It supports

the Gammasphere Users' Executive Committee through surface mailings and E-mail venues. It provides information to users of the 88-Inch Cyclotron as well as the general public through the World Wide Web, brochures, and newsletters.

The Research Coordination Group also maintains the electronics module pool and several data acquisition and analysis computers. Upgrade and modernization of the data acquisition system has been occurring regularly over the course of the last several years.

Non Nuclear Science Research

The 88-Inch Cyclotron is a major source of heavy-ion beams for Single-Event Effect (SEE) testing of solid-state components for the U.S. space program. Because of the ability to run "cocktails" of beams, enabling switches from one ion to another in a matter of minutes, it is possible to quickly establish the energy deposition level at which a SEE will occur. The availability of proton beams, used for studying radiation effects on charge-coupled devices, has further increased the demand for use of the Cyclotron.

The Aerospace Corporation, in cooperation with 88-Inch Operations, has installed a specially instrumented scattering chamber on a dedicated beam line in Cave 4b. A trailer has been installed above Caves 4a and 4b to serve as a counting area for applied programs in those caves. A thin scintillating film transmission detector has been built to measure the beam flux and a beam energy measurement system was adapted from the SuperHILAC for use in the Cyclotron beam lines. These improvements have enabled us to support a large number of small companies and projects who otherwise would not be able to use the Cyclotron.

The radiation biology program continues to use a small amount of beam time annually. The effect of radiation on cells is studied through the use of high-energy protons, helium, and nitrogen. The Irradiation Station built for the biomed studies has also been used extensively by the high energy physics community to study radiation damage in parts being designed for the Atlas detector at the LHC at CERN.

Table 1. FY97 88-Inch Cyclotron Operating Statistics.**Accelerator Operation Summary**

Research	6243 (hours)
Tuning	500
Machine Studies	112
Unscheduled Shutdowns	257
Scheduled Shutdowns	1548
Electrical Energy Consumption (GWH)	8.5
Cost of Electrical Energy (Thousands of Dollars)	616

Experiment Summary

Beam Utilization for Research	
Nuclear Research	5233 (hours)
Atomic Physics	0
Biology and Medicine	90
High Energy Physics	27
Other Research	<u>893</u>
Total	6243

Nuclear Science Research

Universities	15
DOE National Laboratories	5
Foreign Institutions	20
Other government labs	1
Number of Experiments	85
Number of Scientists Participating	164
Number of Students	61

Non-nuclear Science Research

Institutions and Companies	25
Number of scientists and engineers	113
Total users (all research)	332

Percentage of Beam Time (all research) (NOTE THE
NUMBERS BELOW ARE NOT YET CORRECTED
FOR FY97)

In-House Staff	40%
Universities	17%
DOE National Laboratories	12%
Companies	5%
Foreign Institutions	11%
Other government labs	<u>15%</u>
Total	100%

Table 2 88-Inch Cyclotron Beam List

Ion ^a	High Energy b (MeV/ u)	Typical Current @ High Energy (eμA)	Typical Current @≈5–6 MeV/u (eμA)
p	55	6.	20.
d	32	0.7	20.
³ He	45	10.	10.
⁴ He	32	2.	8.
⁷ Li	23	0.4	1.
⁹ Be	25	0.15	1.
¹¹ B	26	0.05	1.
¹² C	32	0.01	12.
¹⁴ N	32	0.03	5.
¹⁶ O	32	2.	20.
¹⁹ F	24	0.1	3.
²⁰ Ne (22)	27	0.1	4.
²³ Na	25	0.01	0.07
²⁴ Mg (25,26)	23	0.7	3.
²⁷ Al	23	0.07	4.5
²⁸ Si (29,30)	22	0.1	2.
³¹ P	22	0.25	2.
³² S (34)	22	0.2	4.
³⁵ Cl (37)	24	0.01	5.
⁴⁰ Ar	23	0.04	23.
³⁹ K	22	0.03	1.8
⁴⁰ Ca	23	0.04	2.5
⁴⁵ Sc	20	0.023	0.22
⁴⁸ Ti	20	0.03	0.6
⁵¹ V	19	0.03	0.4
⁵² Cr	18	0.03	0.6
⁵⁵ Mn	18	0.03	0.3
⁵⁶ Fe (54)	18	0.03	0.5
⁵⁸ Ni	18	0.02	0.3
⁵⁹ Co	17	0.006	0.2
⁶³ Cu (65)	17	0.04	0.4

Table 2. Continued

Ion ^a	High Energy ^b (MeV/u)	Typical Current @ High Energy (eμA)	Typical Current @ ≈5–6 MeV/u (eμA)
⁶⁴ Zn	16	0.02	0.2
⁸⁴ Kr (78,82,86)	14	0.005	6. ^b
⁹⁰ Zr	12	.005	0.2
¹⁰⁷ Ag	11	0.007	0.2
¹²⁰ Sn (118)	9	0.002	0.1
¹³² Xe	8	0.005	0.3 ^c
(129,131,136)			
¹³⁹ La	8	0.002	0.03
¹⁵⁴ Sm	7	0.07	0.07 ^b
¹⁵⁹ Tb	7	0.006	0.006
¹⁶² Dy	7	.07	.07 ^b
²⁰⁹ Bi	5	0.005	0.005
²³⁸ U	4	0.002	0.002

a) Most abundant isotope is listed. Other isotopes run from natural feed are shown in parentheses. Their intensities are proportional to the isotopic abundance, and their high energy values proportional to $1/A^2$.

b) Current for isotopically enriched sample.

c) Higher energies beams are available at lower intensities for $M > 16$.

The following ions have been run at the 88-Inch Cyclotron using isotopically enriched source material. The intensity is proportional to enrichment factor and currents for the same element in the table:

¹³C, ¹⁵N, ¹⁸O, ^{21,22}Ne, ^{33,34,36}S, ³⁶Ar, ^{44,48}Ca, ⁶⁴Ni, ⁷⁰Ge, ^{78,86}Kr, ¹³⁶Xe

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